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Study of nonlinear interactions between counterpropagating shear Alfvén waves

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1 Background and Motivation

Nonlinear effects associated with Alfvén waves are important in laboratory, space, and astrophysical plasmas. Large amplitude Alfvén waves can modify the background plasma density through ponderomotive forces [Shukla et al., 2004; Dasgupta et al., 2003; Bellan and Stasiewicz, 1998; Stasiewicz et al., 2000; Chaston et al., 2000], which arise due to spatial gradients in the wave electric field pressure. Field-aligned density cavities in the presence of strong magnetic fluctuations have been observed in the magnetosphere by the FAST satellite [Chaston et al., 2000, 2003]. Alfvén waves are in turn effected through interactions with field-aligned density structure. Field-aligned density cavities can act as wave guides for Alfvén waves [Mishin and Forster, 1995], channeling Alfvén wave energy. Density structures can also scatter Alfvén waves, acting as an antenna excited by incident waves [Drozdenko and Morales, 2001]. It has been proposed that ponderomotively driven density structure can lead to enhanced dissipation and nonlinear saturation of toroidal Alfvén eigenmodes (TAE's) in tokamaks [Chen et al., 1998]. Alfvén waves can also accelerate plasma particles [Kletzing and Hu, 1994; Lysak and Song, 2003; Chaston et al., 2003; Shukla et al., 1996] and cause heating [Hasegawa and Chen, 1975; Stix and Palladino, 1958]. The acceleration of electrons responsible for the aurora could be due to Alfvén waves [Hasegawa, 1976; Lysak and Song, 2003; Stasiewicz et al., 2000]. Alfvén waves are used to heat ions, through cyclotron resonance, and electrons, through Landau damping, in magnetically confined plasmas for fusion [Horton et al., 2000; Hasegawa and Chen, 1975; Stix and Palladino, 1958]. It has recently been proposed that nonlinear Alfvén waves with frequency below the cyclotron frequency can resonantly heat ions [Chen et al., 2001], which could explain anomalous ion temperatures in magnetic confinement experiments [Gates et al., 2001]. Alfvén waves have been proposed as an explanation for solar coronal heating [Moriyasu et al., 2004; Whitelam et al., 2002].

From a weak turbulence point of view, nonlinear interactions between Alfvén waves are responsible for the cascade of energy in MHD turbulence [Kraichnan, 1965; Ng and Bhattacharjee, 1996]. In incompressible MHD, an anisotropic energy cascade results from interactions between counter-propagating shear Alfvén waves [Shebalin et al., 1983; Goldreich and Sridhar, 1997]. With the inclusion of plasma compressibility, finite amplitude Alfvén waves are unstable to the parametric decay instability [Hasegawa and Chen, 1976; Spangler et al., 1997], where an Alfvén wave decays into a forward propagating ion acoustic wave and a backward propagating Alfvén wave. Parametric decay is thought to be important in the solar corona and solar wind, where it can generate a spectrum of inward (back toward the sun) propagating population of shear waves [Turkmani and Torkelsson, 2004]. A counter-propagating spectrum of Alfvén waves in the solar wind is desirable to explain the observed turbulent spectrum in terms of an incompressible cascade. Dispersion due to finite frequency ($\omega/\omega_{ci} \sim 1$) introduces two cousins of the parametric decay instability, the modulational instability and the beat instability [Wong and Goldstein, 1986; Hollweg, 1994]. The modulational instability is the decay of a shear Alfvén wave into a forward propagating sideband Alfvén wave and a driven nonlinear density fluctuation at the sideband separation frequency.

The research which has been funded by this DOE Plasma Physics Junior Faculty Development Award has focused on an experimental study of nonlinear interactions between shear Alfvén waves. This effort has made use of the Basic Plasma Science Facility (BAPSF) at UCLA. The PI has been given experimental time of roughly 2 to 3 weeks per year of the covered period on the Large Plasma Device (LAPD) to complete this research. The most important results of this research incude:

1. The development of sources of large amplitude Alfvén waves to enable nonlinear physics to be investigated

2. The first laboratory observation of a nonlinear interaction between Alfvén waves

2 Large amplitude Alfvén wave sources

In order to investigate nonlinear phenomena associated with Alfvén waves, a source of large amplitude waves needed to be developed. Two sources of waves were successfully developed: a driven resonant cavity (the Alfvén wave maser) and loop antennas driven by novel broadband, high-power amplifiers.

The cathode and semi-transparent anode of the LAPD plasma source form a resonant cavity which can support shear Alfvén waves. Spontaneous emission from this cavity (an Alfvén wave MASER) is observed when the discharge current is raised above a threshold [Maggs and Morales, 2003; Maggs et al., 2005]. The shear waves emitted by the cavity are eigenmodes of the LAPD column. We have performed measurements of the structure of these eigenmodes and they are consistent with theoretical predictions for eigenmodes in a cylindrical column [Maggs et al., 2005]. The emitted waves can be large amplitude ($\delta B \sim 1 - 2$G, $\delta B/B \sim 0.5\%$) but are only spontaneously excited under certain conditions (high current, low magnetic field) and the timing and duration of emission is not easily controlled. In order to control the timing, duration, amplitude, and frequency of emission, we have driven the cavity externally by applying an oscillating current between the anode and cathode. Using modest levels of power in the oscillating current, we are able to drive waves with comparable or larger amplitude than those generated by spontaneous emission. This technique has allowed the flexible creation of large amplitude Alfvén waves in LAPD, enabling a study of nonlinear interactions between these waves.

Very large amplitude waves can be generated with the driven resonant cavity, however the parameters of these waves are limited by the resonance condition of the cavity (in particular the frequency of the wave is set by the resonant frequency). In order to access a broader range of frequencies, a second wave launching technique was explored: simple current loop antennas driven by the same broadband push-pull drivers used to excite the cavity resonance. These antennas get around the current limitation found in disk exciters used in previous wave experiments in LAPD [] by driving current in conductors inserted into the plasma rather than driving current in the plasma itself. However, it was expected that the parallel wavelength of the launched wave (and hence the frequency) would be set by the antenna size (parallel to the field), and that only a limited range of frequencies would be accessible. Interestingly, this was not observed experimentally. An antenna of 30 cm length was used to launch waves with a wide range of frequencies (wavelengths up to 5 meters) with surprising efficiency. In fact, using a modest driving power, waves with amplitudes comparable to or surpassing that available from the cavity resonance were generated (up to 10G). The ability to drive large amplitude waves using these antennas significantly expands the parameter range of waves available for studies of nonlinear interactions. The most important parameters are the frequency of the waves and the perpendicular scale of the wave (which is observed to be set by the perpendicular scale of the antenna, unlike the parallel scale). The perpendicular scale is important in nonlinear interactions – for example, the strength of a three wave interaction between shear waves is expected to scale as $(\delta B/B)(k_\perp/k_\|)$ [Goldreich and Sridhar, 1997].

The PI was co-author on a paper about the Alfvén wave maser as a result of this work:

> J.E. Maggs, G.J. Morales, and T.A. Carter, "An Alfvén wave maser in the laboratory," Phys. Plasmas **12**, 013103 (2005)

In addition, articles are in preparation describing the properties of waves emitted by the driven cavity as well as on antenna generation of Alfvén waves. These articles are part of the thesis work of Brian Brugman, and should be submitted in early 2007.

3 Nonlinear interaction between shear Alfvén waves

The development of sources of large amplitude Alfvén waves has allowed the first laboratory observation of a nonlinear interaction between these important waves [Carter et al., 2006]. In particular, a co-propagating beat-wave interaction between shear Alfvén waves has been observed. Two large amplitude waves are observed to beat together and drive a density perturbation at their difference frequency. The density perturbation then scatters the Alfvén waves, resulting in the creation of sidebands. The first observation of this interaction was made during simultaneous spontaneous emission of two frequencies (two azimuthal modes) by the maser. Multimode emission (spontaneous emission of two or more waves with different azimuthal wave numbers) is often observed early in time [Maggs et al., 2005]. In some circumstances, the multimode emission persists and two large amplitude Alfvén waves are simultaneously emitted from the source. During this multimode emission, the observed fluctuation spectrum contains many sidebands around the maser emission frequencies as well as a low frequency fluctuation at the sideband separation frequency (and harmonics). As the initial wave amplitudes are increased (by increasing the discharge current), the size of the driven low frequency fluctuation and its harmonics grows, as does the number of sidebands. The observation is consistent with the following scenario:

1. Two large-amplitude Alfvén waves are simultaneously emitted from the source region.
2. The waves have differing azimuthal mode numbers and therefore different phase velocities (due to the dispersive nature of kinetic Alfvén waves). The waves therefore pass through another and create a beat wave.
3. The plasma responds nonlinearly to the beat wave, generating a density perturbation at the beat frequency.
4. The incident Alfvén waves then interact with the low-frequency density perturbation, leading to the creation of sideband Alfvén waves.

In order to confirm that this phenomena is due to the beating of two waves emitted by the maser, controlled studies were conducted where one or two waves of the interacting pair were driven externally. These driven wave experiments show sideband generation and low frequency density fluctuations which are very similar to the spontaneous two-wave interaction previously observed [Carter et al., 2006]. The frequency of the driven wave was varied to study the dependence of the interaction on frequency separation. The interaction is observed over a range of frequency separations, only limited by the Q of the cavity (the driven wave amplitude drops off as we try to drive off-resonance).

The use of antenna-driven Alfvén waves has allowed this study to be expanded over a wider range of wave frequency, amplitude, and perpendicular structure. Important observations include:

1. The strength of the interaction scales bilinearly with the wave amplitudes, as expected. However, the absolute magnitude of the driven density perturbation is substantial, with the normalized density perturbation larger in strength than the normalized amplitude of one of the pump Alfvén waves ($\delta n/n \gtrsim \delta B/B$)

2. As the interaction is studied over a wider range of beat frequency, a resonant-like response in the interaction strength is observed. The peak response occurs at a beat frequency that varies with plasma parameters.

A theory has successfully been developed to explain the magnitude of the interaction and the resonant behavior with beat frequency. The theory is based on several key assumptions consistent with the experimental parameters: a two-fluid description, that the waves have $k_\perp \gg k_\parallel$, and that $\beta \ll 1$. The nonlinear theory predicts that the low-frequency perturbation is Alfvén wave like (an off-resonance Alfvén wave), with resonant behavior when the frequency and wavenumber of the driven perturbation matches the Alfvén dispersion. In addition, the theory predicts a sizeable density fluctuation response. Even ignoring the resonant denominator, the predicted density fluctuation is $\delta n/n \sim \delta B/B$ for parameters similar to the experiment. The physical interpretation of the theory result is that the nonlinearity is primarily the convective nonlinearity and not a ponderomotive nonlinearity: that the drive for the density response is perpendicular, not parallel to the background field. The disparity in $k_\perp$ and $k_\parallel$ allows for cross-field motion (the nonlinear ion polarization drift) to generate the strong density response to the beat wave.

Future work will focus on exploring counter-propagating interactions between Alfvén waves. In addition, during large amplitude wave launch, evidence for strong electron heating, electron acceleration, and background density modification is observed and these phenomena will be studied. Starting in summer of 2006, this ongoing work is funded by an NSF CAREER award.

The report of this first laboratory study of nonlinear interactions between Alfvén waves was made in *Physical Review Letters*:

> T.A. Carter, B. Brugman, P. Pribyl, W. Lybarger, "Laboratory observation of a nonlinear interaction between shear Alfvén waves," Phys. Rev. Lett. 96, 155001 (2006).

A full paper on the spontaneous and driven interaction results is in preparation. In addition, papers outlining the antenna experiments and the interaction theory are in preparation for submission.

4 Educational Activities

The Ph.D. research of one graduate student, Brian Brugman, has been supported by this award. Brian begin his work with the project as a first year, and so did not complete his dissertation by the end of the project period. However, he is poised to graduate in January of 2007. His work has focused on understanding the observed nonlinear interaction through scaling experiments and theory. He is currently writing his dissertation and will be submitting a few first author papers based on his dissertation work. Undergraduate researchers have also been involved in the project. UCLA undergraduates Govinda Escobar and Matt Khalil worked on development of hardware (antennas, probes) and electronics (high-power drivers, amplifiers for probes) that was used for measurements on LAPD. In addition, during the summer, students participating in UCLA's NSF funded REU program participated in hardware construction, experiments and data analysis.

5 Presentations

5.1 Seminars and Colloquia

1. "Nonlinear interactions between shear Alfvén waves in a laboratory plasma," California State University Northridge, Physics Department Colloquium (2004).
2. "Nonlinear interactions between shear Alfvén waves in a laboratory plasma," Princeton University, Seminar, Plasma Physics Laboratory (2004).
3. "Nonlinear interactions between shear Alfvén waves in a laboratory plasma," University of Texas, Austin, Seminar, Physics Dept. (2005).
4. "Nonlinear interactions between shear Alfvén waves in a laboratory plasma," University of Wisconsin, Madison, Seminar, Physics Dept. (2005).
5. "Nonlinear interactions between shear Alfvén waves in a laboratory plasma," University of California, Irvine, Seminar, Physics Dept. (2005).
6. "Nonlinear interactions between shear Alfvén waves in a laboratory plasma," Los Alamos National Laboratory, Physics Division (P24) (2006)
7. "Nonlinear interactions between shear Alfvén waves in a laboratory plasma," Columbia University, Department of Applied Physics (to be given, 2006)

5.2 Conference presentations

1. T.A. Carter, B. Brugman, P. Pribyl, W. Dorland, "Study of nonlinear interactions between shear Alfvén waves in a laboratory plasma," IPELS conference, Whitefish, MT (2003).
2. T.A. Carter, B. Brugman, P. Pribyl, W. Dorland, E. Quataert, "Study of nonlinear interactions between shear Alfvén waves in a laboratory plasma," APS DPP meeting, Albuquerque, NM (2003).
3. B. Brugman, T.A. Carter, P. Pribyl, "Nonlinear interactions between shear Alfvén waves in LAPD," APS DPP meeting, Albuquerque, NM (2003).
4. **INVITED:** J.E. Maggs, G.J. Morales, T.A. Carter, "Laboratory Realization of an Alfvén wave MASER," APS DPP meeting, Albuquerque, NM (2003).
5. **INVITED:** T.A. Carter, "Nonlinear interactions between shear Alfvén waves in a laboratory plasma", URSI National Radio Science meeting, Boulder, CO (2004)
6. B. Brugman, T.A. Carter, W. Lybarger, P. Pribyl, "Studies of nonlinear interactions between Alfvén waves in LAPD," Transport Task Force meeting, Salt Lake City, UT (2004).
7. B. Brugman, T.A. Carter, S. C. Cowley, P. Pribyl, W. Lybarger, "Parametric Interactions between Alfven waves in LaPD," APS DPP Meeting, Savannah, GA (2004).
8. T.A. Carter, B. Brugman, W. Lybarger, P. Pribyl, S.C. Cowley, "Studies of nonlinear interactions between shear Alfvn waves in a laboratory plasma," APS DPP Meeting, Savannah, GA (2004).
9. W. Lybarger, T.A. Carter, B. Brugman, P. Pribyl, "Studies of a driven Alfvnic cavity and cylindrical Alfven eigenmodes in LAPD," APS DPP Meeting, Savannah, GA (2004).

10. B. Brugman, T.A. Carter, “Nonlinear Alfvén Wave Interactions on the Large Plasma Device,” APS DPP Meeting, Denver, CO (2005).

11. **INVITED:** T.A. Carter, “Nonlinear interactions between shear Alfvn waves in a laboratory plasma,” APS April Meeting, Dallas, TX (2006).

12. **INVITED:** T.A. Carter, “Nonlinear interactions between shear Alfvén waves in a laboratory plasma,” Sixth International Workshop on Nonlinear Waves and Turbulence in Space Plasmas, Fukuoka, Japan (2006).

13. T.A. Carter, B. Brugman, D. Auerbach, “Studies of large amplitude Alfvén waves and wave-wave interactions in LAPD”, APS DPP Meeting, Philadelphia, PA (2006).

14. B. Brugman, T.A. Carter, S. Cowley, D. Auerbach, “Nonlinear Alfvén wave interactions in the Large Plasma Device,” APS DPP Meeting, Philadelphia, PA (2006).

15. D. Auerbach, T.A. Carter, B. Brugman, “Electron Heating and Acceleration from High Amplitude Driven Alfvén Waves in the LAPD,” APS DPP Meeting, Philadelphia, PA (2006).

16. **INVITED:** T.A. Carter, “Nonlinear interactions between shear Alfvén waves in a laboratory plasma,” IGPP 6th Annual International Conference on Turbulence and Nonlinear Processes in Astrophysical Plasmas, Oahu, HI (to be presented, March 2007).

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